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LA-UR-87-3998

CONF-8708141--6

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LA-UR--87-3998

DE88 003147

TITLE PERSONAL OVERVIEW OF SOLAR WIND 6

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SUBMITTED TO Solar Wind 6 Proceedings, Held in Estes Park, CO
24-28 AUG 1987

Los Alamos

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PERSONAL OVERVIEW OF SOLAR WIND 6

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The organizers have asked me to provide my views on some of the highlights and, perhaps, lowlights of this meeting. Given the diversity of topics covered, ranging from the acceleration of the solar wind and stellar winds in general through the termination of the solar wind in a distant heliospheric shock, with energetic particle acceleration, interstellar ion pickup, slow mode shocks, coronal mass ejections (CMEs) and their manifestations, and other topics in between, it is impossible for a single person to do justice to all the material presented at this meeting in a short talk. My comments will thus be limited to a few subjects of personal interest.

Beginning first with solar wind acceleration theory, Holzer and Leer have separately reviewed theoretical progress since the early work of Parker in the late 50s and early 60s. Both speakers emphasized that conduction models alone are incapable of explaining *in situ* observations of the solar wind, and that complexities such as diverging field geometries and nonthermal energy deposition are probably required for a complete theoretical picture. Their work indicates that when the major nonthermal energy deposition occurs above the critical point where the expansion becomes supersonic the flow speed is increased at 1 AU, but the mass flux does not increase substantially. On the other hand, when the nonthermal energy deposition occurs primarily below the critical point the mass flux increases at 1 AU but the flow speed generally decreases. Withbroe suggested that if most of the nonthermal energy coming up from the base of the corona is in the form of waves then the dissipation length should be proportional to the particle density raised to some power. He thus expects that within coronal streamers where the density is high waves should dissipate most of their energy low in the atmosphere, and within coronal holes where the density is low the wave dissipation should occur high in the atmosphere. That is, his expectation is that the nonthermal energy deposition is primarily below the critical point within coronal streamers and above the critical point within coronal holes. Such a deposition pattern leads naturally to lower flow speeds and higher mass fluxes from coronal streamers and higher flow speeds and lower mass fluxes from coronal holes, as is inferred from *in situ* observations at 1 AU. More work needs to be done to see if this suggestion has merit, but I believe the idea is worth pursuing.

Both Holzer and Leer point out that one of the problems with current theoretical models is that they have a difficult time explaining the relatively constant mass flux that emanates from coronal holes. As reported by Feldman and coworkers a number of years ago, the specific mass flux at 1 AU is roughly the same (to within a factor of 2 or 3) from one coronal hole to the next. It is also relatively constant from one side of a hole to the other. On the other hand, most models suggest that the mass flux at 1 AU should be quite sensitive to boundary conditions at the base of the corona. How can this observational/theoretical discrepancy be resolved? Are boundary conditions within coronal holes more uniform than generally assumed, or are the models lacking an essential ingredient that makes the expansion within coronal holes relatively insensitive to boundary conditions?

Turning now to energetic particles, there continues to be considerable attention given to the problem of particle acceleration at collisionless shocks. Scholer pointed out a controversy concerning seed populations in interplanetary space. One school of thought suggests that the seed population for acceleration is a background sea of moderately energetic particles already present in interplanetary space at some low level. The other school suggests that the solar wind thermal population itself may provide the seed particles. As noted by Quest at this meeting, there is ample evidence in both observations and simulations that a subset of particles from the solar wind thermal population do get accelerated to relatively high energies by interaction with a collisionless shock. The acceleration process is initiated either by reflection at the shock or by leakage of shock-heated particles from the downstream region to the upstream region. On the other hand, there is also evidence that a low level of energetic particles is usually present in space, and that these particles participate in the acceleration process at shocks. I believe the real question is: What is the relative importance of these two suggested seed populations at different energies? Do both contribute importantly at all energies or is one of these populations the dominant one? We can expect to hear more on this controversy in the future.

A continuing theme in both the invited papers as well as in the poster papers was the important role that waves play in particle acceleration at shocks. These waves can be intrinsic to the interplanetary medium (that is, they can be unrelated to any shock), or they can be produced by instabilities driven by particles accelerated at the shock. In either case, waves act to scatter the accelerated particles, keeping them close to the shock for a sufficiently long time for appreciable acceleration to occur. Without such scattering it is difficult to explain observed particle intensities at many collisionless shocks.

Another theme which was reiterated several times is that shocks do not generally propagate out through interplanetary space with constant θ_{Bn}, where θ_{Bn} is the angle between the shock normal and the upstream magnetic field. Rather, θ_{Bn} varies continuously owing both to the large scale spiral structure of the interplanetary magnetic field and to the presence of upstream fluctuations in the field. As I have just noted, the shock may itself be responsible for some of these upstream fluctuations. In any case, a particular shock that locally is quasi-perpendicular may be quasi-parallel elsewhere in space or time and, of course, vice versa. Thus, one must use care in interpreting measurements of (for example) energetic particle intensities or anisotropies solely in terms of the local field geometry at the shock at the time it is crossed by a spacecraft; the temporally variable, global field geometry at the shock may be an equally important factor to consider in some situations.

Drury reviewed some of the effects that energetic particles accelerated by a shock might have on shock evolution. In astrophysical situations, where Mach numbers can be very high, the pressure associated with accelerated particles may be a significant fraction of the ordinary thermal and field pressure, and thus may appreciably influence the evolution of the shock. Modifications of this sort are actually observed at the Earth's bow shock, but the effects are relatively minor. Typically the solar wind is decelerated by 10–50 km/s (a 3–15% effect) as it transits the so-called foreshock of the Earth's bowshock (that is, the region upstream of the shock populated by waves and accelerated particles). To the best of my knowledge, these effects have not been reported for interplanetary shocks propagating out from the sun. On the other hand, such shocks generally have considerably lower Mach numbers than does the Earth's bow shock.

Moving on now to the distant heliosphere, observations were reported at the meeting which indicate that solar wind high speed stream structure is nearly washed out, at least in the ecliptic plane, at a distance of 25 AU from the sun. The process by which stream structure damps with increasing heliocentric distance is pretty much as predicted by Hundhausen and several others a number of years ago on the basis of observations at 1 AU. Initially a high speed stream steepens for the simple reason that the faster-moving plasma at the crest of the stream overtakes slower-moving plasma ahead. However, this steepening is resisted by pressure forces which grow at the leading edge of the stream as the result of the steepening process. The compression region formed by steepening eventually is bounded by a forward-reverse shock pair at distances beyond several AU from the sun. At all heliocentric distances momentum and energy is transferred from the fast plasma in the stream to the slower plasma ahead via the pressure forces associated with the compression region, so that the high speed plasma is decelerated and the slow speed plasma is accelerated. This process of momentum and energy transfer is nearly complete by 25 AU, and what is left are the remnants of the pressure waves, as noted by Burlaga and colleagues. I think that the interesting point of all this is that this is probably the simplest possible mechanism that one might imagine to damp out the organization of the solar wind represented by stream structure, and it appears to work very well. In my opinion, much of the complexity of the appearance of the outer heliosphere is not associated with complexity in basic physical processes, but rather is related to the fact that the sun often provides a non-simple stream structure to begin with.

Lazarus reported that a slow, systematic oscillation in meridional flow with a period of about 25 days is sometimes present in the Voyager data obtained far from the sun. Whether or not this modulation in north-south flow is somehow related to the decay of streams with increasing heliocentric distance or to some other process is presently uncertain, but this oscillation effect bears further investigation.

In a poster paper Möbius reported on observations of interstellar material, primarily helium, picked up by the solar wind. The interstellar material penetrates into the heliosphere as neutrals, is ionized by solar photons and by charge exchange, and is then picked up by the solar wind flow and transported to the outer reaches of the heliosphere. The pick-up process for newly ionized interstellar material is essentially identical to the pick-up process which occurs at comets and at Venus. The picked up ions eventually fill a thick shell in velocity space with radius approximately equal to the solar wind speed and centered on the solar wind bulk flow speed. There is considerable evidence to suggest that these picked up interstellar particles are the seed population for the so-called anomalous cosmic ray component discussed at this meeting and elsewhere. There is not yet any direct evidence that the pick-up of interstellar material causes any substantial slowing of the solar wind flow (as does, for example, the pick-up of cometary material at comets), presumably because the amount of interstellar material picked up is small. It remains to be seen whether or not interstellar pick-up produces any substantial slowing of the solar wind flow in the very distant heliosphere.

As the years go by one gains a greater appreciation for how much solar wind variability is organized by position relative to the heliospheric current sheet which encircles the sun. At this meeting this was perhaps most dramatically demonstrated by the global interplanetary scintillation measurements of the San Diego group. Their measurements, which extend over all longitudes and up to latitudes of about 60 degrees and which cover the period from 1972 to the present, clearly illustrate how the average solar wind speed is organized relative to the current sheet. Low speeds are observed near the current sheet, and progressively higher speeds are observed with increasing distance (angle) from it. Similar variations have, of course, been reported using *in situ* observations; the latter measurements reveal that quantities such as particle density and helium abundance also are strongly organized according to position relative to the current sheet. In addition, at this meeting Cummings demonstrated that intensity of the anomalous cosmic ray component likewise is modulated by position relative to the current sheet, at least in the outer heliosphere.

Finally, Smith has suggested that position relative to the current sheet may explain the so-called period-doubling effect reported by Burlaga. The term period-doubling as used by Burlaga refers to the fact that IMP and ISEE at 1 AU observed two stream interaction regions per solar rotation while simultaneously Voyager at 15 AU observed one stream interaction region per solar rotation. Burlaga suggested that this period-doubling (from $\sim$13.5 days to 27 days) might be related to the period-doubling which is a characteristic of the progression towards turbulence in some nonlinear, dissipative systems. However, this analogy is clearly incorrect since in nonlinear dynamics the term "period-doubling" refers to a doubling of the number of fundamental frequencies (periods) present in a system rather than to a doubling of a fundamental period as in the Earth/Voyager observations. It is Smith's suggestion that the period-doubling reported by Burlaga is more apparent than real and is most probably associated with the fact that Earth and Voyager were at considerably different latitudes (that is, different distances from the current sheet) at the time of the observations reported by Burlaga. Earth and Voyager thus were embedded in considerably different stream structure to begin with.

Tuesday evening Hundhausen provided us with a very provocative lecture on the subject of coronal mass ejections (CMEs). He emphasized that many CMEs seem to consist of 3 distinct parts: (1) an outer loop; (2) a broad central cavity or depletion; and (3) a prominence embedded within the cavity. It is his opinion that the cavity plays a role in the outward propagation of CMEs that is not generally appreciated. He points out that if a CME is initiated by a gradual readjustment of the global coronal field as suggested by a model worked out by Low, then the cavity, which normally envelopes a prominence in coronal streamers, will rise in the solar atmosphere because it is less dense than the surrounding corona, and therefore buoyant. In this picture it is the buoyancy of the cavity that drives a CME outward from the sun; the prominence is merely along for the ride and is not the driving agent for the CME.

It is my opinion that the scenario suggested by Hundhausen has considerable merit. Nevertheless several questions can be raised. First, how general is the three-part CME structure described? We heard comments during the discussion that well defined cavities are clearly present in only about 50-60% of all CME events. Are the cavities present but obscured by line-of-sight effects in a substantial fraction of the other events? If not, what drives these other CMEs outward away from the sun? Second, where do large flare events fit into this picture? When one looks at height versus time diagrams one often finds that the very fast CMEs associated with large flares decelerate as they move away from the sun whereas the CMEs associated with prominences generally accelerate with height in the solar atmosphere. These very different types of velocity-height profiles suggest that different acceleration mechanisms may be operating.

I should note that to the best of my knowledge a three-part structure has not yet been reported for CMEs in the solar wind at 1 AU or at other heliocentric distances. (Although there are problems in identifying CMEs with *in situ* observations as the talks by Neugebauer and Klein have emphasized, it is my opinion that we can usually recognize these events using a combination of plasma and field measurements.) In particular, I am not aware that one can usually distinguish between loops and cavities in the observations, perhaps because these features tend to become "washed out" with increasing distance from the sun. On the other hand, prominence material has been identified in the solar wind on several occasions by the presence of He^+ within shock drivers. The relative rarity of events where He^+ can be detected in substantial amounts is consistent with the fact that prominences generally occupy only a small fraction of the total volume of CMEs. It is also consistent with the fact that for most CMEs most of the prominence material that is present is usually heated to coronal temperatures (thus one observes He^{++} rather than He^+) by the time the prominence reaches 5 solar radii above the solar surface.

Hundhausen suggested that there perhaps has been too much emphasis placed on trying to establish an association between CMEs and shocks in the solar wind. I tend to agree. It is my opinion that the association of big, fast CMEs with interplanetary shocks is relatively trivial. Although it is nice to see this association firmly established, did anyone really believe that such CMEs would not drive interplanetary shocks, particularly since it has been known for many years that there is an excess mass flux associated with most shock disturbances at 1 AU? Of more interest is the nature of the CMEs themselves in the solar wind. How can CMEs be identified? Why do they have the anomalous signatures that have been reported (for example, temperature depressions, enhanced helium abundance, unusual ionic states, bidirectional streaming electrons and protons, and strong, smoothly varying magnetic fields)? What is the fate of the slower CMEs, which account for a substantial fraction of all CMEs? Are such CMEs important to the overall mass, momentum, and energy budget of the solar wind?

In partial defense of the emphasis on shock events, it is generally true that shock events are among the largest of all interplanetary disturbances, and generally produce the largest geomagnetic disturbances and the largest modulations of galactic cosmic rays. Shocks are also ideal sites for particle acceleration. For these reasons alone shock disturbances are worth studying and understanding, including their initiation in disturbances at the sun. In addition, shocks provide an excellent fiducial mark. If we want to be know what CMEs look like in the solar wind and how they evolve with distance from the sun, the best place to start the study is with shock events because we have good reason to believe that most shocks at 1 AU are driven by fast CMEs. (This is not true in the outer heliosphere.) Further, work to date suggests that slow CMEs in the solar wind at 1 AU are relatively uninteresting objects. If our present identification of slow CMEs is correct, then the preliminary result is that slow CMEs do not usually produce important geomagnetic effects, nor do they appear to make a particularly important contribution to the overall mass, momentum, and energy budget of the solar wind at 1 AU.

In a couple of the poster papers, McComas and I suggested that magnetic field draping about fast CMEs in the solar wind might have some interesting consequences. The concept of draping has been with us for a number of years, but I do not believe that (1) the possible consequences of draping about CMEs have been adequately explored or (2) anyone has ever proven with observations that this draping actually occurs. Our work in this area indicates that draping might contribute importantly to producing extended intervals when the interplanetary magnetic field is strongly southward and therefore may be an important factor in stimulating geomagnetic activity. Further, field asymmetries associated with draping may produce important dynamical effects in interplanetary space, and draping may cause prolonged intervals of nearly radial fields in the outer heliosphere.

An important question that was scarcely touched upon at this meeting is: Do CMEs retain their magnetic connection to the sun as they propagate out into interplanetary space, or do they disconnect to form closed plasmoids? Beginning with Skylab there has been very little direct evidence for magnetic disconnection from the sun in coronagraph observations. On the other hand, without disconnection from the sun how can a catastrophic build-up of magnetic flux in interplanetary space be avoided? Can the magnetic flux newly drawn out by a CME be balanced by field line closure elsewhere in interplanetary space? (This amounts to reconnection.) Can we somehow distinguish between disconnected plasmoids and attached magnetic bottles in the *in situ* 1 AU observations? It is my personal opinion that CMEs at 1 AU are generally best interpreted in terms of detached plasmoids, but more work needs to be done to decide the issue. And, I must confess, I have a difficult time reconciling this opinion with what I know of the temporal evolution of the appearance of CMEs as documented in coronagraph photographs.

In his tutorial talk, Hundhausen drew a schematic picture of what a typical interplanetary shock disturbance associated with a fast CME might look like. The schematic was an updated version of one he first drew at Solar Wind 2, and in keeping with the notable lack of hard evidence for magnetic disconnection from the sun, the CME itself in this picture extends from about 0.1 AU behind the shock all the way back to the vicinity of the sun. Here I would like to note that the anomalous plasma and field signatures (such as, for example, bidirectional streaming electrons) that one normally uses to identify CMEs in the solar wind at 1 AU typically persist for only about 12 hours, and seldom last longer than a day. If we interpret this persistence as a measure of radial thickness, then these signatures correspond to CMEs with radial widths which typically lie in the range from $\sim$0.05 to 0.20 AU. That is, the typical CME at 1 AU appears to be much more confined in the radial direction than Hundhausen's sketch would suggest. However, this radial width may be more apparent than real if the "legs" which (may) magnetically connect a CME to the sun do not share the anomalous signatures of the remainder of the CME or if the "legs" are spatially confined and hence seldom encountered

As many of us know, there has been a continuing controversy over the frequency of CMEs and their associations with various forms of solar activity. In particular, there is a controversy concerning the solar cycle dependence of the frequency with which the sun emits CMEs. These issues were addressed at least partially in the talks by Howard and Sime. Feynman added new fuel to the fire in her poster paper. There she showed that geomagnetic sudden storm commencements, which are known to be strongly associated with interplanetary shocks which are, in turn, usually driven by CMEs at 1 AU, have had an occurrence pattern throughout the 20th century that closely follows the sunspot cycle. This is indirect evidence that at least the fastest CMEs (that is, those with speeds sufficiently high relative to the ambient solar wind to produce shocks) wax and wane in frequency in the ecliptic plane roughly in phase with sunspots and, by inference, with solar activity in general. Of course, a study such as this can not address the question of how the overall frequency of CMEs varies with the solar cycle since many CMEs have relative speeds which are too low to produce shocks at 1 AU, and the fraction of slow CMEs apparently varies considerably throughout the solar cycle. Nor does a study such as this address the question of what specific forms of solar activity CMEs are preferentially associated with.

Several hours of the meeting were devoted to the subject of slow mode shocks. Richter enumerated at least 5 good reasons why slow mode shocks should be rare at heliocentric distances greater than about 0.5 AU. Since the Lindau group has been able to identify only a few examples of slow mode shocks in the Helios solar wind data obtained between 0.3 and 1.0 AU, it does not appear that slow shocks are particularly important entities in the solar wind at heliocentric distances greater than 0.3 AU. On the other hand, it has been suggested by Hundhausen, Holzer, and Low that slow mode shocks might form in front of many CMEs as they propagate out through the corona due to the fact that CMEs typically have outward speeds that considerably exceed the local sound speed but that are lower than the local Alfven speed. Interestingly, they suggest that these slow shocks would have fronts that are concave outward; such concave fronts can sometimes be inferred from coronagraph observations. It is generally believed that slow mode shocks should evolve into fast mode shocks as they propagate outward to greater distances from the sun owing to the substantial drop in Alfven speed with increasing heliocentric distance; Whang gave a poster paper presenting a model of how this evolution might occur. Noting that the decay signature of a slow shock would include a rotational discontinuity behind a fast shock, Kennel suggested the observation of this paired signature would be strong evidence in favor of slow mode shock formation close to the sun.

Despite the aforementioned enthusiasm for the possibility of slow mode shocks ahead of CMEs as they propagate outward through the corona, Steinolfson presented the results of some of his numerical simulations of CME disturbance propagation in the corona which indicate that slow mode shock formation does not generally occur. It is his contention that slow mode shocks are not required to divert the ambient corona and solar wind around a CME, and it is his belief that the coronagraph observations can be explained consistently in terms of fast mode waves propagating in front of CMEs. The jury is still out on this controversy; I am sure we will be hearing more on this topic in the future.

There was very little mention of solar wind ionic composition in the oral sessions at this meeting, but there were at least two posters on this topic which I think illustrate the capabilities of a new generation of instruments to resolve the various charge states of most of the predominant solar wind species. The University of Maryland group, in particular, showed results from AMPTE where they have resolved all of the various charge states of carbon and oxygen in the solar wind. This type of measurement should become more common if and when new flight opportunities arise, and will provide us with a tool for probing temperatures deep within the solar wind source regions.

Finally, I was particularly struck while listening to the oral sessions of how few of the talks actually included presentations of *in situ* observations of the solar wind. It is my opinion that this lack of emphasis on the *in situ* observations to a large extent more accurately reflects the organization of the meeting than a dearth of new observational results. However, Neugebauer showed a viewgraph documenting the steady decline of solar wind observations in the 1980's. The downward trend is truly sobering; unless it is reversed in the near future and unless new measurement capabilities are pursued vigorously, solar wind research as many of us have come to know it may wither away and die.

Acknowledgment. I thank A. J. Hundhausen, D. J. McComas, and M. F. Thomsen for their comments on a draft of this talk. This work was performed under the auspices of the U.S. Department of Energy with support from NASA under S-04039-D.